

PARAMETER OPTIMIZATION OF CUTTING FORCE IN CORN STALK CHOPPING

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ABSTRACT

Corn is cultivated mostly in all countries for its high consumption, quality, and food value. Corn residuals, including stalk and cob, are also considered as the most abundant biomass resource and animal feeding. Shortening corn stalks into different sizes is an important pre-process to make animal food and biomass. Reducing shearing force is one of the most effective way to save energy in such process. This paper presents experimental results to optimize the cutting force by varying approach angle and feed angle, the two parameters representing the relative motion of the stalk and the cutter. Optimum design of experiments were planned through three stages: screening, steepest descent and optimal experiments. Compared to a typical condition in commercial choppers, where these angles are usually set to be 0°, the optimal setting provided a five-time smaller cutting force. The results obtained thus is very promising for further studies to optimize devices of forage cutting.

KEYWORDS: Corn Stalk; Forage Chopping; Animal Feed; Biomass; Cutting Force & Cutting Optimization

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INTRODUCTION

Being the third important crop after rice and wheat, corn is generally cultivated around the world. Corn residuals, including stalk and cob, are also considered as the most abundant biomass resource and animal feeding (Demirbas, Balat, & Balat, 2009; C. Y. Li, Jia, Zhang, & Wang, 2013). Shortening corn stalks into different sizes is an important pre-process to make animal food and biomass energy. For example, the segment size requirement should be 6.4 mm for gasification (Raman, Walawender, Shimizu, & Fan, 1981), 1 mm for chemical conversion (Van Walsum et al., 1996), 5.6 mm for briquetting processes (Mani, Tabil, & Sokhansanj, 2006). Size reduction machines commonly used include hammer mills, knife-mills, disk-mills, forage choppers, and wood chippers (C. Y. Li et al., 2013). The performance of cutting process are usually evaluated through shearing force and energy requirement (Alireza Allameh, 2016; Igathinathane, Pordesimo, Schilling, & Columbus, 2011; M. Azadbakht, 2014). Reducing shearing force is one of the most effective method to save cutting energy.

Several studies have investigated to reduce shearing force in forage size reduction. Some of the most important factors having strong effects on the cutting force have been found to be angles between the cutting tool and the stalk direction. In previous studies, a knife approach angle, sometime called as oblique angle, was defined as the angle between the knife edge and the line perpendicular to the direction of motion of the knife. The shear angle or tilt angle is the angle between the longitudinal axis of the stalk and cutting edge the knife (Ghahraei,

Ahmad, Abdan, Suryanto, & Othman, 2011), (P. Gupta & Oduori, 1992). For sugarcane cutting, an oblique angle of 35° , and a tilt angle of 27° were found to be optimum values using a revolving knife-type base cutter (P. Gupta & Oduori, 1992). Optimum knife edge angle, shear angle, oblique angle, and rake angle were 25° , 40° , 40° , and 40° , respectively for Kenaf stems (O. Ghahraei, 2011).

The effect of blade sharp angle, i.e. the angle between two surfaces of the cutting edge, on cutting force was also implemented. Ghahrae et al. (Omid Ghahrae, 2008) showed that the stalk cutting section with the blade sharp angle of 30° was smooth and without break on filaments. This construction also provided a smaller shear force compared to that of 45° blade angle. For linear knife grid systems, studies of Igathinathane et al. (Igathinathane, Womac, Sokhansanj, & Narayan, 2009) (Igathinathane, 2010) found that the shearing angle has a strong effect on the cutting force and specific energy. In those studies, the tool edges are in the form of a 60-degree V-block. Three values of the shearing angle was investigated at 90° , 45° , 0° . It has been found that, the smallest energy needed when cutting angle is 0 degrees (i.e. the cutting edge is parallel to the axis of corn stalks) has the minimum energy consumption, as only about 6% compared with the case of 90° cutting angle, where the cutting edge is perpendicular to the axis of corn stalks. The results also indicated that the blade sharp angle, blade shape and cutting angle all significantly affected the cutting resistance under the supported cutting condition. A smaller cutting angle was related to a larger cutting resistance.

Another trend for saving cutting energy is to design tool for cutting stalks by simulating (imitating) the texture of nature (M. Li et al., 2015; Tian et al., 2017; Tong, Xu, Chen, & Li, 2017). Tian et al. designed a bionic blade with the cutting profile curve of *B. horsfieldi* palate, resulting in strong cutting ability and good cut quality. Average maximum cutting force and cutting energy consumption for the bionic blade were reduced by 12.89% and 10.73%. Li, Yang (M. Li et al., 2015) employed FEM technique to design and analysis of bionic cutting blades with the geometrical characteristic of the praying mantis's foreleg. Both the simulation and experimental results indicated that the bionic serrate-edge blades showed better performance in cutting efficiency compared with a conventional smooth-edge blade. Nevertheless, making cutting edges in special forms would be difficult and costly for commercial devices.

As can be seen, both approach angle and shear angle play a key role in energy saving for corn stalk cutting processes. Our study found that, beside such parameters, the angle between fiber direction and the line perpendicular to the direction of motion of the knife, hereby called feed angle, also has a strong effect on cutting of corn and other forage stalks. For the best of the authors' knowledge, simultaneous effects of approach angle and feed angle in cutting corn stalks have rarely been found in literature. This paper presents experimental results in evaluating effects of such angles and the optimization process to obtain smallest energy required in corn stalk cutting.

MATERIALS AND METHODS

In order to evaluate the effects of relative orientation of the stalk-to-be-cut and the cutting tool, we introduce the following terms as represented in Figure 1. Figure 1(a) depicts a cutting diagram in the section perpendicular to the fiber lines of the stalk-to-be-cut. The cutting tool, or the knife, has a straight cutting edge. Motion of the knife (1) is represented by a big red arrow in the figure. In a cutting process, the knife (1) moves in a plan (signed as XOY in Figure 1a) which is perpendicular to the fiber orientation of stalk (4). In this plan, the knife approach angle, α is defined as an angle between the knife edge and the line perpendicular to direction of the cutting motion. The axis of the stalk is suggested to be lied in the plan YOZ, which is perpendicular to the plan XOY and shown in Figure 1(b). In the plan YOZ, the feed angle, β , is

defined as the angle between the fiber orientation and the line perpendicular to the cutting motion. Another angle, named shear angle, or tilt angle, is defined the angle between longitudinal axis of the stalk and cutting edge the knife, both are projected on the plan ZOY, is kept to be 90° and not shown here. It would be noted that the two angles, knife approach/oblique angle and shear/ tilt angle, were mentioned and investigated in several previous studies (Ghahraei et al., 2011), (P. Gupta & Oduori, 1992). In this study, the effects of knife approach and feed angles will be examined. These angles are usually set as 0° in commercial devices.

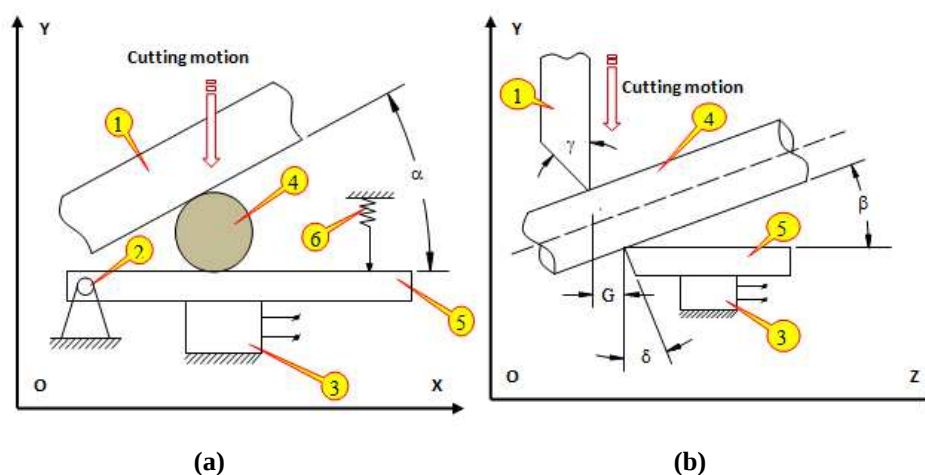


Figure 1: Diagram of Experimental Parameters: (a) Front View and (b) Side View

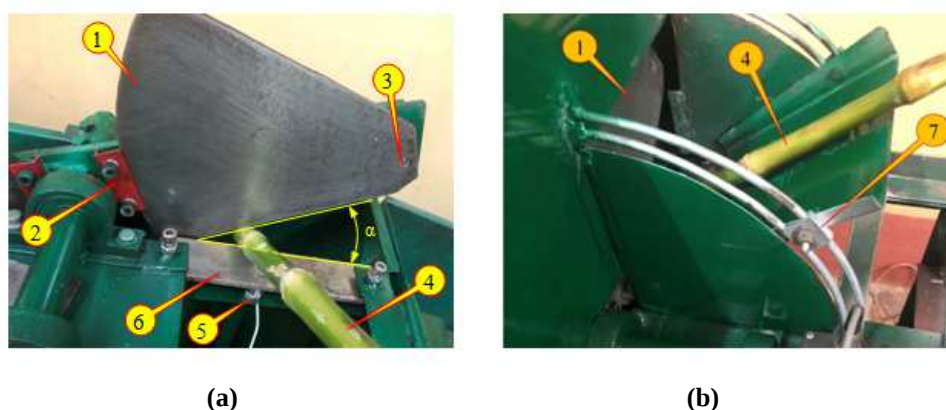


Figure 2: Practical Experimental Setup: (a) a Front View and (b) an Auxiliary View

In Figure 1, the corn stalk to-be-cut (4) is placed between the knife (1) and the countershear (5). The countershear is kept in contact with a dynamic force sensor (3) by mean of a hinge joint (2) and a pre-compressed bolt (6). Signal of cutting force obtained from the force sensor will be collected by a data acquisition system (DAQ) and then analyzed.

The experimental devices are set up by modifying a mini commercial forage chopper. The original knife in the form of a bar was replaced with the one made in the form of circular sector. Figure 2 demonstrates the practical experimental setup. With special structure of the knife (1), the approach angle, α can be easily varied by mean of the clamp (2) and the center bolt (3) (see Figure 2a). Any selected feed angle, β can also be obtained by a guide trough with bolts (7), as shown in Figure 2b. A dynamic force sensor model 9712A500 with a sensitivity of 11 mV/lbf is placed under the countershear bar to collect the cutting force. A DAQ model NI-USB-6008 and the Ni Signal Express software are

employed to collect and save the cutting force data. Minitab® and OriginalLab®softwares are used to design experimental plan and analyze experimental results. Cutting force data were collected in cutting single stalk by extracting the maximum values for each corn stalk with around 81% wet basic.

RESULTS AND DISCUSSIONS

The experimental study were made using three stages: screening, steepest descent and optimum design with response surface experiments (Montgomery, 2006).

Screening Experiments

Screening experiments were made to determine potentially influential variables, to help screen down number of parameters needed to evaluate. In this study, the screening experiments were implemented at a full factorial design with three factors: Approach angle, Feed angle and the gap between the knife and the countershear (see Figure 1b). Coded levels and real values of each factor are depicted in Table 1. Each set of experiments including 8 runs were replicated 3 times.

Table 1: Experimental Factors in Screening Experiments

Level	Approach Angle (°)	Feed Angle (°)	Gap (mm)
Low (-1)	0	0	1
High (+1)	60	50	2

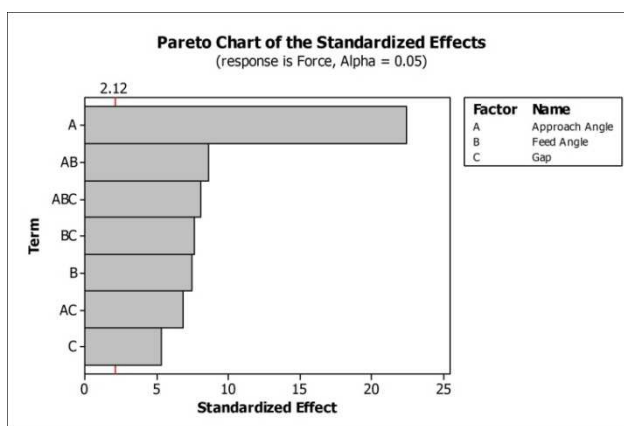


Figure 3: Pareto Chart Obtained from Screening Experiments

The results obtained was then analyzed by Analysis of Variance (ANOVA) technique. The Pareto chart of the effects was used to determine the magnitude and the importance of each factor's effect.

The chart displays the absolute value of the effects and draws a reference line (a vertical red line) on the chart, as shown in Figure 3. Any effect that extends past this reference line is potentially important. As can be seen in Figure 3, the largest main effects are for Approach Angle (factor A), then the Feed Angle (factor B) and lastly for the Gap (factor C). From the screening experiment, we can conclude that the two factors A and B (Approach angle and Feed angle) deserve the most consideration for further investigation in the next stage. The gap should be kept as a constant for its difficulty in varying accurately.

Steepest Descent Experiments

Since initial estimates of experimental factor may be far from the actual optimum, the steepest ascent (or descent) experiments should be made to move rapidly to the general vicinity of the maximum (or minimum) response, in this case is the cutting force. The method of steepest descent is that experiments are proceeded sequentially along the path of maximum decrease in the predicted response. The path of steepest descent requires the direction to be opposite of the sign of the coefficients obtained in the first order response model.

As we want to carry out the optimum parameters where the cutting force is smallest, a steepest descent process is applied. Firstly, an initial experimental design of 2-level full factorial design for the most two important factors, as found in the screening stage, was implemented. Values of these factor are shown in Table 2.

Table 2: Experimental Factors in Screening Experiments

Level	Approach Angle (°)	Feed Angle (°)
Low (-1)	0	0
High (+1)	10	10

The model of cutting force as a response function of the two input factors are depicted in Table 3. Figure 4 presents contour plot obtained from the initial experiments.

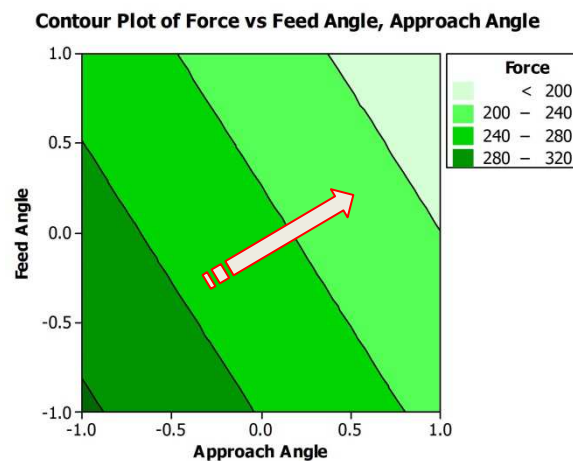


Figure 4: Contour Plot of Initial Experiments

As can be seen in Figure, in order to move quickly to the general vicinity of the minimum cutting force (depicted by a big arrow), the next steepest descent experiments should be planned properly.

Table 3: Coded Coefficients of the Cutting Force

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		248.0	10.8	22.99	0.000	
Approach Angle	-95.1	-47.6	10.8	-4.41	0.002	1.00
Feed Angle	-60.4	-30.2	10.8	-2.80	0.021	1.00

As can be obtained from Table 3, the initial model of the cutting force can be expressed as $y_b = 248.0 - 47.6 \cdot x_1 - 30.2 \cdot x_2$. Hence, the path of steepest descent will result in y_b moving in a positive direction for decreases in x_1 and x_2 . Choosing one unit changed in the coded x_1 scale ($\Delta x_1=1$), the steps along the path of steepest descent are determined as below.

$$\Delta x_2 = \frac{b_2}{b_1} \Delta x_1 = \frac{-30.2}{-47.6} \cdot 1 = 0.63 \quad (1)$$

Converting to real values, each increase of 10° in Approach angle (x_1) will require an increase of 6.3° in Feed angle (x_2). To make it easy in practical varying the experimental factors, incremental steps of approach angle and feed angle were selected as 10° and 7° , respectively. Results of steepest descent experiments are shown in Table 4 and represented in Figure 5.

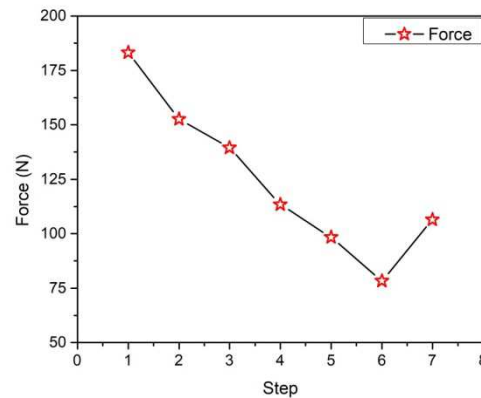


Figure 5: The Cutting Force at Steepest Descent Steps

Table 4: Steepest Descent Experiments

Steps	Approach Angle (°)	Feed Angle (°)	Force (N)
1	20	20	183.1818
2	30	27	152.5661
3	40	34	139.5095
4	50	41	113.3962
5	60	48	98.33087
6	70	55	78.24374
7	80	62	106.3657

As can be seen in Table 4 and Figure 5, the general vicinity of the minimum cutting force would potentially be located around step 6. The final optimum experiments should be implemented nearby this point.

Optimal Experiments

The optimal experiments were implemented follow Central Composite Design (CCD) plan, as shown in Table 5.

Table 5: Design and Results of CCD Optimal Experiments

StdOrder	Approach Angle (°)	Feed Angle (°)	Force (N)	StdOrder	Approach Angle (°)	Feed Angle (°)	Force (N)
1	37.3	38.1	107.79	14	55.0	48.0	87.86
2	72.7	38.1	75.58	15	37.3	38.1	109.86
3	37.3	57.9	81.72	16	72.7	38.1	75.58
4	72.7	57.9	84.93	17	37.3	57.9	78.65
5	55.0	48.0	90.93	18	72.7	57.9	87.00
6	55.0	48.0	90.93	19	55.0	48.0	90.93
7	55.0	48.0	90.93	20	55.0	48.0	90.93
8	30.0	48.0	103.20	21	55.0	48.0	90.93
9	80.0	48.0	75.44	22	30.0	48.0	100.13

Table 5: Contd.,							
10	55.0	34.0	87.86	23	80.0	48.0	75.44
11	55.0	62.0	75.58	24	55.0	34.0	90.93
12	55.0	48.0	87.86	25	55.0	62.0	72.51
13	55.0	48.0	87.86	26	55.0	48.0	87.86

The results was then analyzed by ANOVA technique, as shown in Table 6. Summary of the cutting force model is depicted in Table 7.

Table 6: Analysis of Variance for Cutting Force

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	2409.80	481.96	210.22	0.000
Blocks	1	52.71	52.71	22.99	0.000
Linear	2	1441.08	720.54	314.28	0.000
Approach Angle	1	1041.87	1041.87	454.44	0.000
Feed Angle	1	399.21	399.21	174.13	0.000
Square	1	154.76	154.76	67.50	0.000
Feed Angle*Feed Angle	1	154.76	154.76	67.50	0.000
2-Way Interaction	1	761.25	761.25	332.04	0.000
Approach Angle*Feed Angle	1	761.25	761.25	332.04	0.000
Total	27	2460.24			

Table 7: Model Summary for Cutting Force

S	R-sq	R-sq(adj)	R-sq(pred)
1.51415	97.95%	97.48%	95.83%

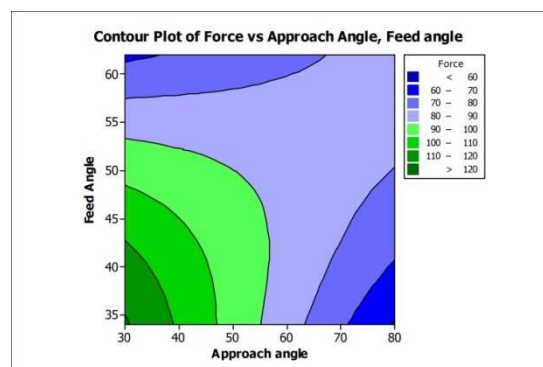


Figure 6: Contour Plot of the Cutting Force

The cutting force was expressed as a function of approach angle, α and feed angle, β as:

$$F = 210.1 - 3.132\alpha^2 - 0.409\beta - 0.03293\beta^2 + 0.05574\alpha\beta \quad (2)$$

This function was then used to carry out the optimal set of input factors so as to obtain smallest cutting force. A contour plot of the force model is shown in Figure 6. From the figure, the smallest cutting force would be obtained as less than 60 N if the approach angle is of 70°-80°, coupled with the feed angle of 35°-40°. Another set of parameters includes 30°-40° approach angle and around 65° feed angle. Compared to a typical case in practice, where commercial choppers use straight knives with both approach and feed angles are set to be 0°, where the cutting force would be higher than 300 N (see Figure 4), optimal input parameters were found to reduce the cutting force by around 5 times. The results obtained in this

paper thus is very promising for further studies to optimize devices for size reduction of corn as well as other forage stalks.

CONCLUSIONS

An experimental study to optimize cutting force in chopping corn stalks was investigated. The following significant remarks would be concluded:

Beside approach angle, the feed angle, which demonstrates the relative orientation of stalks to-be-cut with respects to the cutting motion, has a strong effect on the shearing force when cutting the stalks;

Although approach angle and other parameters have been examined in several previous studies, influence of the feed angle has rarely been found in literature. It has been found that, varying the feed angle also results in changing the cutting force;

The optimized setting of approach angle and feed angle resulted in reducing the cutting force as much as five times, compared to a typical condition where the both two angles are fixed at 0°.

Further studies should be implemented to further optimize the cutting parameters, cutting geometrical form and dynamical conditions such as cutting velocity, feeding rate etc.

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